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A simple field method for stereo-photographic length measurement of free-swimming fish: merits and constraints

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Abstract

A simple field method to correct for bias in stereo-photographic underwater measurements is presented and its usefulness to improve the accuracy of length estimates of free-swimming fish is tested. The calibration is based on the inclusion of stereo exposures of a slate of known dimensions at the beginning and end of each measuring session, and it allows correction for non-parallel optical axes, spherical aberration of the lenses, and for other sources of bias that may vary between sessions. A precision of ±3% for replicate length measurements of a 30 cm slate is obtained at distances between 0.7 and 2.0 m. This compares well with reported values that are obtained with more sophisticated (laboratory) methods. However, application of this calibration does not significantly improve the accuracy of stereo measurements of the length of free-swimming fish (±2.5 cm or 7-11% of actual fish length). The limitations are caused by difficulties in recognizing identical extreme points at the body of fish that are photographed under field conditions. By averaging three or more replicate measurements the accuracy is improved to ±1 cm (2.7-4.5%). We conclude that effort should be aimed at increasing sample size, rather than at improving equipment and correction procedures, when measuring free-swimming fish in their natural habitat.

Keywords: Bias; Fish length; Stereo-photography; Underwater

1. Introduction

Stereo-photography has been applied successfully to determine the three-dimensional organization of fish schools (e.g. Cullen et al., 1965; Pitcher, 1975; Dill

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et al., 1981) or bird flocks (Major & Dill, 1978). The accuracy in these studies is as high as ±0.3 to 3.5% of the measured distances, and is attained by the use of sophisticated equipment and calibration techniques, usually under laboratory conditions. This may explain why the method has hardly been used in field studies on coral reef fishes, where the required facilities are often not available. Quantitative data on the growth of coral reef fishes are scarce (Munro & Williams, 1985; Russ & St. John, 1988; Choat, 1991) and repeated length measurement of reef fishes in their natural habitat seems a useful application of stereo-photography. Its main advantage is that fishes do not have to be captured, which is often difficult and may cause wounds or disturbance affecting the behaviour and growth of the fish (Tesch, 1971; McFarlane & Beamish, 1990; van Rooij et al., 1995).

Stereo-photographic measurement of free-swimming fishes requires the use of two aligned underwater cameras in a portable set up. Klimley & Brown (1983) describe such a set up and point out an important source of bias, which occurs when the optical axes of the two cameras are not exactly parallel. To correct for such bias they present a method that is based on the empirical determination of the linear change in axis separation and the hyperbolic change in image dimension, both in relation to the distance from the camera. They attained an accuracy of ≤5% for repeated measurements of a 50-cm staff, aligned parallel to the stereocamera and photographed in a swimming pool at distances between 2 and 8 m. As recognized by the authors, a shortcoming of their calibration is that it does not correct for spherical aberration in the camera lenses and that the ideal conditions in a swimming pool are not representative for the situation in the field. Moreover, they had no opportunity to compare their length estimates of free-swimming sharks with actual shark lengths.

We used a relatively simple method that allowed us to correct for all sources of bias and to determine the accuracy of our stereo photographic measurements under field conditions. The correction is based on the deviations in the stereo estimates of the dimensions of a PVC slate of known size that was routinely photographed in each session. We determined the accuracy for replicate measurements of the slate and of free-swimming fish of known length. We used this method to measure the growth of the herbivorous reef fish *Sparisoma viride* (Bonnaterre) at the fringing reef of Bonaire (Netherlands Antilles). The results of our growth measurements are reported elsewhere (van Rooij et al. 1995). The focus of this paper is on the merits and constraints of stereo-photography to measure the length of free-swimming fish in their natural habitat.

2. Methods and results

2.1. Equipment and procedure

We used two Nikonos V cameras with 35 mm f/2.5 Nikkor lenses and 100 ASA Fujichrome film for colour slides (24 × 36 mm frames). Both cameras were connected to an automatic TTL strobe (Ikelite Substrobe MV), allowing an aperture-setting of 22 (maximum depth of field) and a shutter time of 1/60 s. The cameras were mounted on an aluminium strip with an upright edge, used for camera alignment. The complete set up is shown in Fig. 1. The trigger system was adjustable, and the cameras were considered to be synchronized when the clicks of the shutters were heard simultaneously. Synchronization was checked by taking a stereo pair of a running stopwatch at the beginning of each session and was always within 0.01 s. The focus of both lenses was always set at the minimum distance (somewhat below 0.8 m). The distance between the two cameras was slightly adjustable and varied between 170 and 175 mm, yielding just enough field overlap to contain a maximum sized fish (<45 cm) at a distance of about 0.7 m.

Fishes were always photographed from a lateral view and from an estimated distance between 0.7 and 2 m, while they were swimming, using the stereo set up hand held. Parrotfishes normally swim at low speed (<1 body length $\cdot s^{-1}$) with their pectoral fins, so that their body is hardly curved during swimming and they can be easily followed by a diver. If possible, at least three replicate shots were taken per fish.

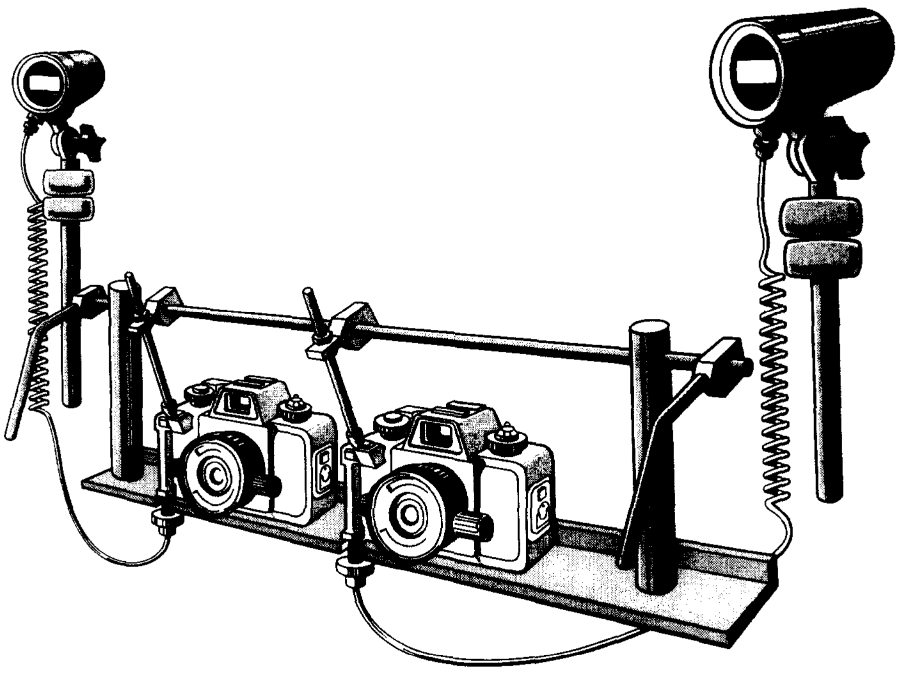

Fig. 1. Simplified representation of the stereo-camera set-up for underwater use. Shown are two Nikonos V cameras with 35 mm Nikkor lenses, mounted and aligned on an aluminium angle, and connected to an Ikelite substrobe (MV). The trigger system for shutter release is adjustable. In reality a second aluminium strip was fixed just above the cameras for greater rigidity, and both strobes were attached to the handles with an Ikelite arm system. Two buoys below each strobe ensure nearly neutral buoyancy.

A session is defined as a single dive on which some 36 stereo pairs were taken until the films were fully exposed. Films had to be replaced between sessions, which required the cameras to be dismounted. Before and after each session the distance between both cameras was measured to the nearest mm. Care was taken always to remount the same camera/lens combination at the same position (i.e. one camera with the same lens always at the left, the other at the right). Films were developed commercially (E-6 process). The slides were projected with a colour enlarger on white drawing paper, ensuring that the frame edges were projected as well. At a magnification of about 5 × the projected frame edges, the outline of the fish and some characteristic markings on its body were traced with a pencil. The actual magnification factor was calculated as the average of the projected length of upper and lower frame edge divided by 36 mm and the left and right edges divided by 24 mm. The coordinates (see below) of the tip of the snout and the end of the median finray on both exposures of a pair were measured to the nearest mm from the drawing, using a drawing board with adjustable set square. They were divided by the magnification factor to calculate them back to the original 24 × 36 mm scale. The two length estimates obtained from both exposures of a stereo pair never differed more than a few mm and their average was used as the final (uncorrected) stereo estimate.

2.2. Basic calculations

The length of an object on a single photograph can only be determined if the distance from which the exposure was taken is known and the object is parallel to the plane of the film. The clux of stereo-photography is that the distance to any photographed point can be calculated from the relative position of the point on both exposures of a stereo pair. Consequently, the length of an object can be determined, independent of its angle to the film plane, as long as both ends can be distinguished. All that is required is that [1] the distance between the two cameras is known, and [2] the optical axes of the cameras are parallel (Boyce, 1964; van Sciver, 1972). The underlying principles are best explained stepwise.

Step 1: calculating distance of a point. An x-y-z cartesian coordinate system is defined where the optical axis of the left camera is chosen as the z-axis. The x- and y-axes are in the nodal plane, parallel to the horizontal (36 mm long) and vertical (24 mm long) edges of the film frames, respectively. In this system the z-coordinate of a point P (z_P) represents the shortest distance between P and the nodal plane, which is the parameter to be calculated. Fig. 2 shows the geometrical relationships between P and its projections (P_l' and P_r') on the films of two cameras with parallel optical axes, as seen in the x-z plane. Similar triangulation provides two equations with two unknown parameters (x_P and z_P):

(*a*) $x_P/z_P = d(x_l')/z_F$, and (b) $(x_P - x_C)/z_P = d(x_r')/z_F$

where x_C is the distance between the two cameras, z_F the focal distance, and $d(x_l')$ and $d(x_r')$ represent the difference between the x-coordinate of the optical axis

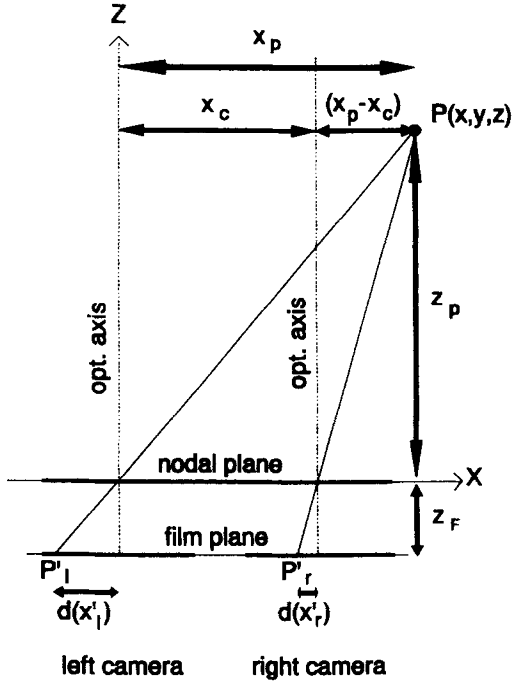

Fig. 2. Schematic of the geometrical relationships between a point P (black dot) and its projection (P'_1 and P'_2) on the films of a stereo pair of cameras, used to calculate the z-coordinate (or object distance, z_P) of the point: $z_P = [z_F \times x_C]/[d(x'_l) - d(x'_r)]$.

and that of P′ for the left and right camera, respectively. Substitution of (a) in (b) yields the equation:

$$z_P = [z_F \times x_C]/[d(x'_l) - d(x'_r)] \tag{1}$$

[equivalent to Eq. (2) in van Sciver, 1972]. Note that the same equation is obtained when P lies in between or to the left of both optical axes. The demoninator in Eq. (1) represents the horizontal displacemetnt of P'_l relative to P'_r, as seen when both film frames are superimposed. z_F must be multiplied by the refraction index of water in case of underwater use. With the focus set at minimum distance z_F was 48.8 mm: 35 mm (the focal distance of the lenses) plus 1.7 mm (the outward displacement of the lens due to focussing), multiplied by 1.33, the approximate refraction index of water.

Step 2: calculating x- and y-coordinates of the point. Once z_P is known, the x- and y-coordinates of P can be calculated from those of its projection P′ by similar triangulation:

$$(x_{P'}/x_P) = (z_F/z_P) = (y_{P'}/y_P).$$

The x- and y-coordinates of P′ can be measured on both exposures, so two length estimates are obtained from a single stereo pair.

Step 3: calculation length of object. The first two steps can be repeated for both ends of an object. From the x-y-z-coordinates of both ends the length of the object (L) can be calculated (following the Pythagorean theorem) as:

$$L = \surd\left[\mathrm{d}^2(x_\mathrm{P}) + \mathrm{d}^2(y_\mathrm{P}) + \mathrm{d}^2(z_\mathrm{P})\right] \tag{2}$$

where the d^2 terms represent the squared difference between the coordinates of both ends.

2.3. Calibration slate lengths

The first and last few underwater exposures of each session were taken of a 21 × 30 cm PVC slate, positioned approximately parallel to the film plane with the long sides oriented horizontally, at distances between 0.7 and 2 m. Using Eq. (1), z_P was calculated for the four corners of the slate, and Eq. (2) yielded estimates of the length of each of the four sides. A side was considered to be parallel to the plane of the film if the z_P values for both ends did not differ more than 2 cm. For parallel sides the correct z-coordinate (z_cor) can be calculated directly from the relationship:

$$z_\mathrm{cor}/z_{\mathrm{P}'} = L/L'$$

where L is the actual length of the side and L' the average length of its projection on both exposures (equivalent to Eq. (1) in van Sciver, 1972). Distance of the parallel slate sides calculated this way (z_cor) is plotted against the estimates obtained by Eq. (1) (average of both ends, $\bar{z}_\mathrm{P}$) in Fig. 3. Linear regression yielded the equation:

$$z_\mathrm{cor} = (0.931 \times \bar{z}_\mathrm{P}) + 92.4\ (\mathrm{mm}) \tag{3}$$

$$(n = 59,\ \mathrm{R}^2 = 0.955,\ p < 0.001).$$

The slope of the fitted line is significantly less than 1 ($t_{57} = 2.57$, $p < 0.01$), indicating that Eq. (1) underestimates distances below 1.34 m. Eq. (3) was used to correct all z_P values, which were subsequently used in Eq. (2) to calculate distance-corrected lengths. Fig. 4A shows the deviations of the uncorrected stereo measurements (of the 30 cm long slate sides) from the actual lengths (125 values obtained from all slate exposures). Maximum deviation amounted to ±3 cm, and there was a significant correlation with $\bar{z}_\mathrm{P}$. The deviations of the distance-corrected estimates were no longer correlated with $\bar{z}_\mathrm{P}$ and most had decreased to <2 cm (Fig. 4B).

We discovered a slight but consistent deviation between the precision of the estimates of the long (horizontal) sides of the slates and the short (vertical) sides, probably due to spherical aberration of the lenses. Furthermore, the bias in the x- and y-dimensions proved to be relatively constant within sessions and more

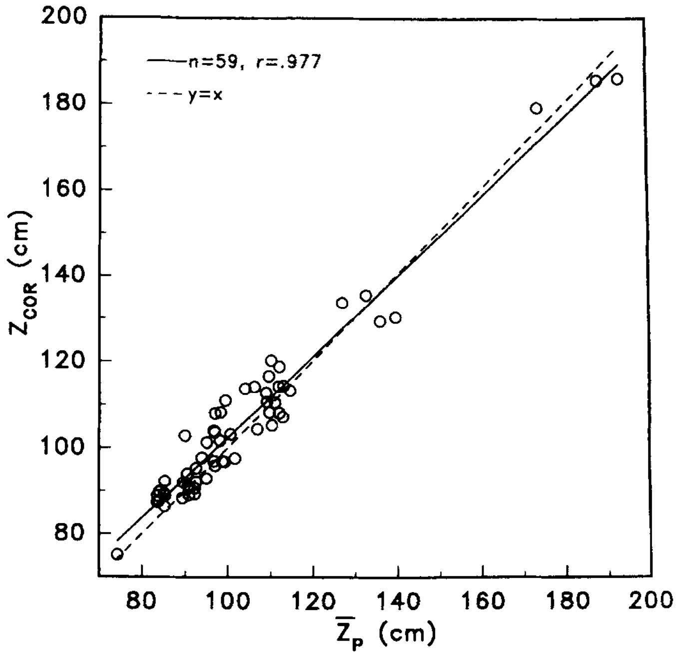

Fig. 3. Plot plus fitted regression line of distance of parallel slate sides (z_{cor}, calculated from the relationship $z_{cor}/z_{p'} = L/L'$) versus $\bar{z}_p$ (average z_p of both ends, calculated from Eq. (1)); $z_{cor} = (0.931 \times \bar{z}_p) + 0.92.4$ ($R^2 = 0.9546$, $p < 0.001$).

variable among sessions. This is probably caused by small changes in the relative position of the two cameras, as unavoidable when changing films between sessions. Therefore, the slate measurements were used to calculate separate correction factors in the x- and y-dimensions for each session:

$$corF_x = 300\ \mathrm{mm}/\bar{L}_l \text{ and } \mathrm{cor}F_y = 210\ \mathrm{mm}/\bar{L}_s$$

where $\bar{L}_l$ and $\bar{L}_s$ are the averages of all stereo measurements of the long and short sides obtained during that session. Applying the corrections for distance and for distortion in the x- and y-dimension, an adapted version of Eq. (2) is obtained:

$$L_{cor} = \sqrt{\{[\mathrm{cor}F_x \times \mathrm{d}(x_p)]^2 + [\mathrm{cor}F_y \times \mathrm{d}(y_p)]^2 + [\mathrm{d}(z_{cor})]^2\}}. \quad (4)$$

Fig. 4C shows how the final stereo estimates of the slate lengths calculated from Eq. (4), deviate less than 1 cm (or 3%) from the actual length in 124 out of 125 cases.

2.4. Calibration fish lengths

Due to potential curvature of the fish, we expected that the stereo measurements would underestimate actual fish length. To determine the magnitude of this

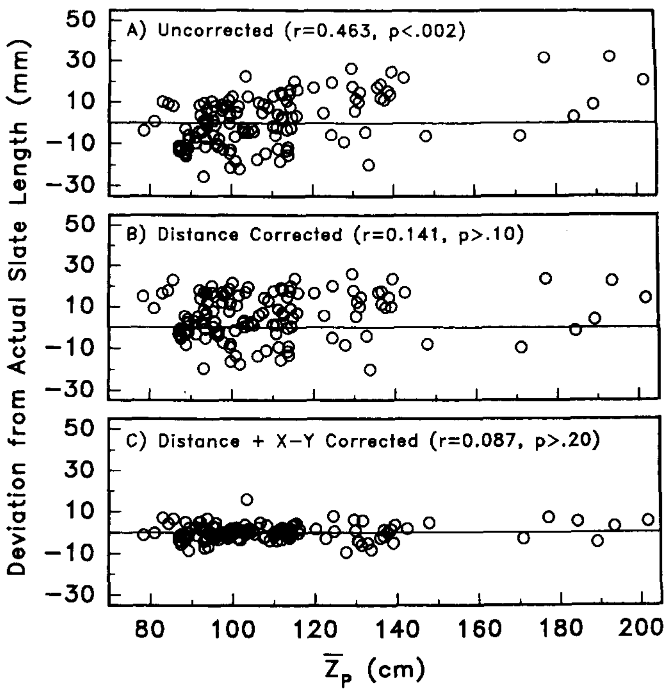

Fig. 4. Deviation (in mm) of estimated from actual slate lengths (30 cm long) for 125 estimates, (A) without any correction, (B) after correction for distance, and (C) after additional correction for distortion in the x- and y-dimension. Plotted against estimated distance $\bar{z}_p$ (average z_p of both ends). Coefficients and significance of the correlation with distance shown.

deviation and to allow a correction for it, L_{cor} was compared with the actual length (L_{lab}) of fish that were caught and measured shortly before or after the stereo-photographic measurement (Fig. 5). Linear regression yielded the relationship:

$$L_{cor} = (0.948 \times L_{lab}) + 17.0 \text{ (mm)}$$

$$(n = 80,\ R^2 = 0.9245,\ p < 0.001).$$

The slope deviates significantly from 1 ($t_{78} = 1.68$, $p < 0.05$) and, contrary to expectation, the stereo measurements tend to overestimate the length of (the smaller) fish. Since the error in L_{cor} will be larger than that in L_{lab}, the regression of L_{lab} on L_{cor} would not fit the classical regression model (cf. Sokal & Rohlf, 1981). Therefore, the final corrected fishlength (L_{fish}) was calculated from the inverse relation, as:

$$L_{fish} = 1.054 \times (L_{cor} - 17.0) \text{ (mm)}. \qquad (5)$$

Fig. 6 shows the deviations of the stereo measurements from the actual fish lengths without any correction [cf. Eq. (2), Fig. 6A], after the slate-based

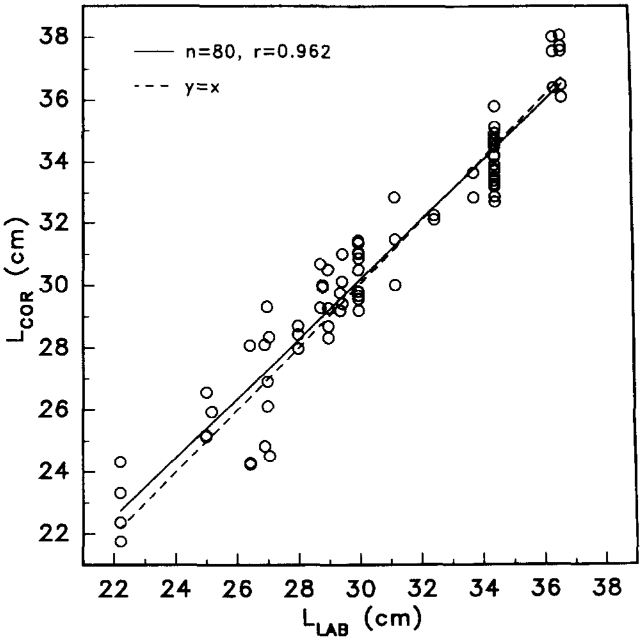

Fig. 5. Plot plus fitted regression line of L_{cor} for fish [length calculated from Eq. (4)] and actual length (as measured in the laboratory, L_{lab}): $L_{cor} = (0.948 \times L_{lab}) + 17.0$ mm ($R^2 = 92.45\%$, $p < .001$).

corrections [for distance and distortion in the x- and y-dimension, cf. Eq. (4), Fig. 6B], and after the additional fish-based calibration [cf. Eq. (5), Fig. 6C]. The figure shows how the correlation with distance is removed after the slate-based corrections. However, all corrections yield only a limited improvement in accuracy. L_{fish} as determined from a single stereo pair may still deviate as much as 2.5 cm (7–11% of fish length). Better results are obtained when replicate measurements are averaged, resulting in deviations of ≤1 cm (or ≤2.7–4.5%) in 21 out of 22 cases (Fig. 6D). The largest deviations occurred for averages, based on only 2 or 3 stereo pairs, and the accuracy generally improved with increasing sample size (see also Fig. 5). Furthermore, the absolute deviations appear independent of fish size, implicating that the relative accuracy (as% of fish length) is largest for the larger fish.

3. Discussion

After the slate-based correction steps, the deviation of stereo measurements from actual slate length was ±1 cm (or 3%) in more than 99% of 125 cases. This compares well with the ±5% precision obtained by Klimley & Brown (1983). An advantage of our method is that it corrects not only for non-parallel optical axes (which the distance correction is assumed to do), but also for spherical aberration

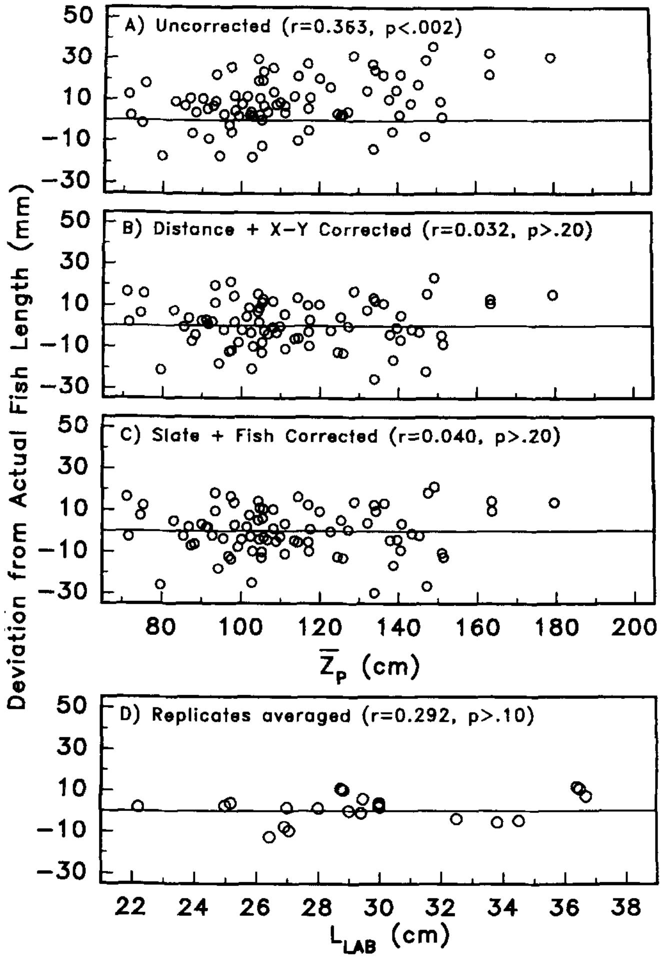

Fig. 6. Deviation (in mm) of estimated from actual fish lengths for 80 estimates (obtained from 22 fish): (A) without any correction [cf. Eq.(2)], (B) after slate-based corrections [cf. Eq.(4)], and (C) after additional fish calibration [cf. Eq.(5)]. Plotted against average distance $\bar{z}_p$ (average z_p of snout and tail; (D) shows the deviations of the averaged replicates for all 22 fish, plotted against actual fish length. Coefficients and significance of the correlations shown.

of the lenses (distortion in the x- and y-dimension) and for sources of bias that may vary between sessions (separate correction factors per session). Furthermore, the practical procedure is relatively simple because no laborious calibration series of an object at fixed angle and distances is needed. Finally, our method requires no determination of the hyperbolic change in image dimension with distance. A limitation is that the focus of the cameras must always be set at the same distance, which means that objects can only be photographed from a limited focal range, as opposed to Klimley & Brown's method. However, in our case this was not a constraint because our fishes were too small to be photographed with enough accuracy at distances exceeding 2 m.

For free-swimming fishes a single stereo measurement could deviate as much as 3 cm from true fish size, and the accuracy was not improved much by the successive correction steps. Most likely, these large deviations are explained by the difficulty of locating exactly the same points on the fish's body at both exposures of a stereo pair. When a fish swims at an angle to the plane of the film, the tip of the snout may be hidden behind a more caudal part of its (convex) head. Because the fish is seen at different angles from the two cameras, different points on the head will appear as the tip of the snout on both exposures. This easily results in an apparent displacement of 1–2 cm of the snout on one exposure relative to the other. Another source of error occurs if the fish is photographed with strong flashlight against a dark background, e.g. when swimming high in the water column. The edge of the film frame may then be hard to distinguish, hindering accurate measurement of the coordinates of the fish snout and tail on the film. This can be prevented, however, by using less strong flash lighting and choosing a suitable background. Another potential source of error is imperfect camera synchronization. However, although more accurate synchronization could be realised (e.g. using cameras with electronically triggered shutter systems or by using a single strong flash light or a slave-driven second strobe), this bias is of relatively minor importance, given the slight displacement of the fish within the 0.01 s maximum asynchrony (4 mm for a 40 cm fish swimming at 1 body length $\cdot$ s^{-1}). Comparison of (corrected) stereo estimates with actual fish lengths showed an apparent lack of curvature of the fishes. This is explained by their pectoral fin swimming mode, during which their bodies are kept rigid. This is not necessarily a prerequisite. Curved fish could be measured by dividing their body in small segments and measuring the length of each segment. However, this is only possible if there are enough distinct points on the fish's body that can be recognized on both exposures, and the accuracy will be reduced. Furthermore, the amount of time needed for measuring the stereo exposures would be greatly increased although this could be offset by the use of a computer-aided image analysis system.

Although a single stereo measurement can deviate considerably from actual fish length, reasonable precision can be obtained by averaging the values of replicate measurements, as shown by the ± 1 cm (or 2.7–4.5%) accuracy of our average estimates.

Improvements in equipment and correction procedures are certainly possible. For example, the optical axes may be more parallel in one session than in the next, and separate distance corrections per session should be preferred. This would require a larger number of slate exposures per session than the 3–6 stereo shots we took. However, our results show that the most important limitations in precision are caused by the fact that one is dealing with free-swimming fishes and not with a conveniently shaped and positioned object. Therefore, such improvements may prove to be of little value. Instead, an increase of sample size (more replicates per individual) seems the most efficient way to improve the accuracy of stereo-photographic length determinations of fishes in their natural habitat.

Restrictions to the successful application of stereo-photography to measure fish length are that the water must be clear enough and the fishes not too shy to take good photographs. Furthermore, only fishes with a laterally flattened body can be measured from virtually any angle; more rounded fishes have to be more or less parallel to the film plane in order to recognize the tip of snout and tail on both exposures. Finally, fishes should preferably keep their body rigid for sufficiently long periods. Besides scarids, many other coral reef fishes seem to comply with these requirements. Our growth measurements of *Sparisoma viride* (van Rooij et al. 1995) showed no difference between results obtained by stereo-photography or by tag-recapture procedures and demonstrate the potential of the method.

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